BELLCOMM, INC.
1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: Relative Effectiveness of Several Materials as Radiation Shields
Case 710

DATE: March 29, 1968

FROM: R. H. Hilberg

ABSTRACT

The effectiveness of lead, iron, aluminum and water at shielding against protons trapped in the earth's magnetic field has been calculated. The calculations have been made for spherical cavities with inside radius varying from 10 cm to 1000 cm and for a model common mission module. For thin walled shields, lighter elements are more effective per unit mass. When wall thickness is comparable with the chamber radius, the denser materials become more effective.

This memorandum was prepared during the Saturn V Workshop Study and supplements Reference 1, "Trapped Radiation Doses" which describes the variability of dose with altitude and inclination.

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MEMORANDUM FOR FILE

Introduction

The dose encountered in a given region of space generally depends on the mass shielding surrounding the system in question. Since many of the results of radiation shielding calculations are expressed in terms of the thickness of aluminum required to provide a given degree of protection, it is useful to present results comparing the effectiveness of aluminum with other possible shielding materials. It is further useful to present total mass values rather than wall thicknesses.

Calculations have provided this information for lead, iron, water and aluminum in the form of spherical shells, and a cylindrical model for a common mission module. Further, the dose rate dependence on total mass is given for a circular earth orbit with 300 nm altitude and 30° inclination. The dependence of dose rate on total mass in other low earth orbits can be estimated from the results of this memorandum in conjunction with Reference 1, prepared for the Saturn V workshop study.

The dependence of dose rate on mass will be different for different proton energy spectra so that the dependence of relative dose rate on shield thickness will not be the same for other types of radiation. However, the relative effectiveness of different materials will not change.

Discussion of Calculations

Two geometric configurations have been considered. The first consisted of a set of spherical caskets which could be used to shield some radiosensitive object like film with inside radius varying from 10 cm to 1000 cm. The other configuration was a cylindrical model for a common mission module. This model had heavy shielding at the ends which was not included in the values quoted and had an outside diameter of 20 feet. The length of the module was 12.5 feet.

For the spherical configuration the total required mass is evaluated by means of the expression:

$$M = 4\pi\rho R^2 t \left(1 + \frac{t}{R} + \frac{1}{3}\left(\frac{t}{R}\right)^2\right)$$

For the cylindrical CMM model the mass is given by:

$$M = 2\pi\rho hRt\left(1 - \frac{t}{2R}\right)$$

In the above expressions: ρ is the density of the shielding material (g/cm^3);

R is the container radius (inside radius for the spherical caskets, outside radius for the CMM) (cm);

h is the height of the CMM (cm);

t is the wall thickness (cm), determined from range-energy curves.

For protons in the energy range 1 MeV to several hundred MeV, which is the range of primary interest in considering manned spaceflight hazards, the dominant interaction producing energy losses is ionization. The theory of this type of interaction has been well-developed and is described in some detail in Evans (Reference 2). The rate of energy loss is given by:

$$\frac{dE}{dt} = \frac{4}{m_o}\frac{z^2 e^4}{V^2} NZ \left[\ln\left(\frac{2m_oV^2}{I}\right) - \ln(1-B^2) - B^2\right] \text{ ergs/cm}$$

where: m_o is the rest mass of the electron,
z is the nuclear charge of the incident particles,
e is the charge of the electron,
V is the velocity of the incident particle,
N is the number of target atoms per cm^3,
Z is the atomic number of the target material,
B is the ratio of the velocity of the incident particles to the speed of light,
I is the ionization potential of the target material.

The values of I used in Reference 3 and which have been evaluated experimentally are:

MATERIAL	I
Aluminum	163 eV
Iron	285 eV
Lead	826 eV
Water	65.1 eV

Range energy curves based on these values are shown in Figure 1.

From the above equation one can see that the stopping power of a given piece of shield is proportional to NZt which is the number of electrons/cm^2 which penetrating protons see on their paths through the material. This can be written as

$$NZT = \frac{\eta \rho t\ Z}{A}$$

where: η is Avagadro's number
ρ is the shield density
A is atomic weight of the shield
t is the shield thickness, in cm

The above relationship indicates that for a given thickness, expressed in grams/cm^2 (i.e. $x = \rho t$), the stopping power and the range depend on the ratio of atomic number to atomic weight. In general, for light nuclei, excluding hydrogen, this quantity is about one half. For heavier nuclei, the number of neutrons increases more than the number of protons so that this ratio becomes considerably less than one half (e.g., .38 for lead).

Since the ionization potential varies with atomic number, the range is not accurately proportional to A/Z. An empirical relation for the dependence of range on atomic weight is called the Brag-Kleeman rule which states that the range is approximately proportional to the square root of the atomic weight. This rule is also discussed briefly in Reference 2. It can also be used to get an effective range for mixtures or compounds by using:

$$\sqrt{A_{Mixture}} = \frac{\Sigma Ni Ai}{\Sigma Ni \sqrt{Ai}}$$

and the expression:

$$R_{Mixture}^{(cm)} = \frac{\sqrt{A_{Mixture}}}{\sqrt{Ao}} \frac{\rho o}{\rho_{Mixture}} Ro\ (cm)$$

The validity of these rules is shown in Figure 1 where:

$$R, \frac{1}{\sqrt{A}} R \quad \text{and} \quad \left(\frac{Z}{A}\right) R$$

have been plotted for aluminum, iron and lead. It is seen that neither rule is ideal over the whole range of energies shown.

The following values for density were used for the materials considered:

WATER	1.00 grams/cm^3
ALUMINUM	2.7 grams/cm^3
IRON	7.9 grams/cm^3
LEAD	11.4 grams/cm^3

The proton energy spectrum used for the calculations is that described by Vette (Reference 4) for a circular orbit at 300 nm altitude and 30° inclination. The integral energy spectrum is shown in Figure 2.

Results

The dose rate in a circular orbit with 300 nm altitude and 30° inclination is given as a function of total mass for the spherical caskets and the model CMM in Figures 3 and 4. The scarceness of high energy spectral data makes extrapolation of these curves much beyond the limits shown somewhat questionable. However, in the regions shown, the uncertainty in dose rate should be less than a factor of two.

The relative effectiveness of lead, iron, water and aluminum as shielding materials is shown for the geometrical configurations discussed above in Figures 5 through 12. The curves represent the mass of each material required to provide the same shielding as a given amount of aluminum. Also shown is the thickness of aluminum corresponding to a total mass of aluminum. Since the range-energy data and density data needed for these calculations are very well known, the values given in these figures are uncertain by less than 10%.

Conclusions

Where the wall thickness is a small fraction (e.g. $<10\%$) of the radius of the chamber, the mass of material needed to provide a given degree of shielding increases with the atomic number of the shielding material. For such a thin shell case, the total mass is equal to the area multiplied by the required areal density given in Figure 1. Water gives the lightest weights and lead the heaviest. Iron shields are about 20% heavier than aluminum ones. Polythene is about 10% lighter than water would be and may be more convenient in some applications than water. For the CMM model with R = 300 cm, the thin shield approximation is always valid for meaningful calculations.

When the wall thickness becomes comparable to the chamber radius, one can no longer treat the wall as a thin shell. In such cases, shielding is less efficient per unit mass because of geometric effects; therefore, the denser materials become better relative to the lighter ones. The crossover point for aluminum, water and iron occurs for the spherical configuration when the wall thickness is about one-fourth of the inside radius. Lead becomes as effective as aluminum when the required thickness of aluminum is about half the inside radius.

R H Hilberg

1011-RHH-cas R. H. Hilberg

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From: R. H. Hilberg

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References

1. R. H. Hilberg, "Trapped Radiation Doses" - Case 710, Bellcomm Memorandum for File, March 7, 1968

2. R. D. Evans, "The Atomic Nucleus", Chapters, 18 and 22 McGraw-Hill, 1965

3. C. W. Hill, W. B. Ritchie and K. M. Simpson, "Data Compilation and Evaluation of Space Shielding Problems; Range and Stopping Power Data" - Volume 1 ER 7777 Lockheed Nuclear Products, 1965

4. J. I. Vette, "Models of the Trapped Radiation Environment", Volume I, "Inner Zone Protons and Electrons", NASA SP-3024, 1966

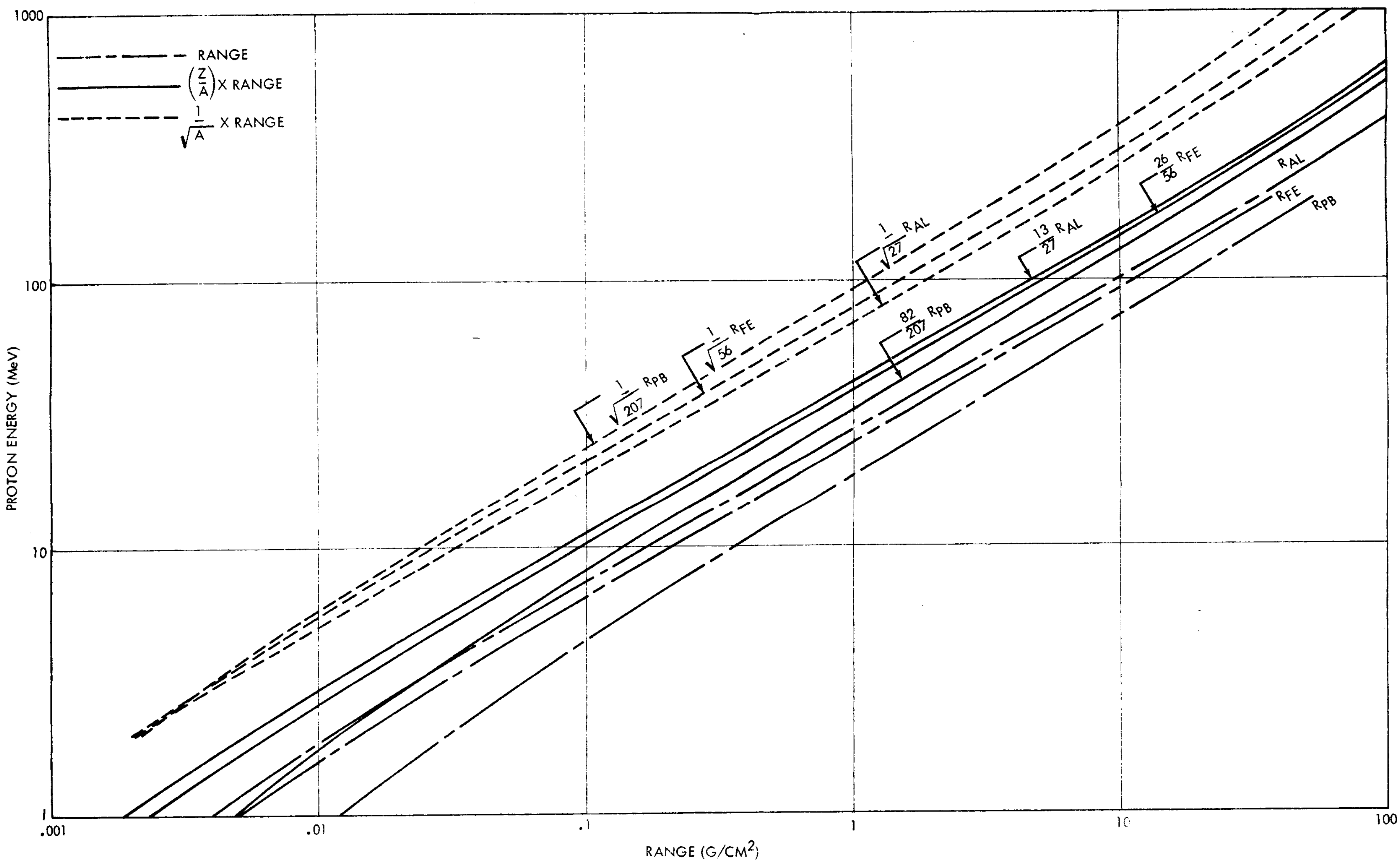

FIGURE 1 - PROTON RANGE ENERGY CURVE

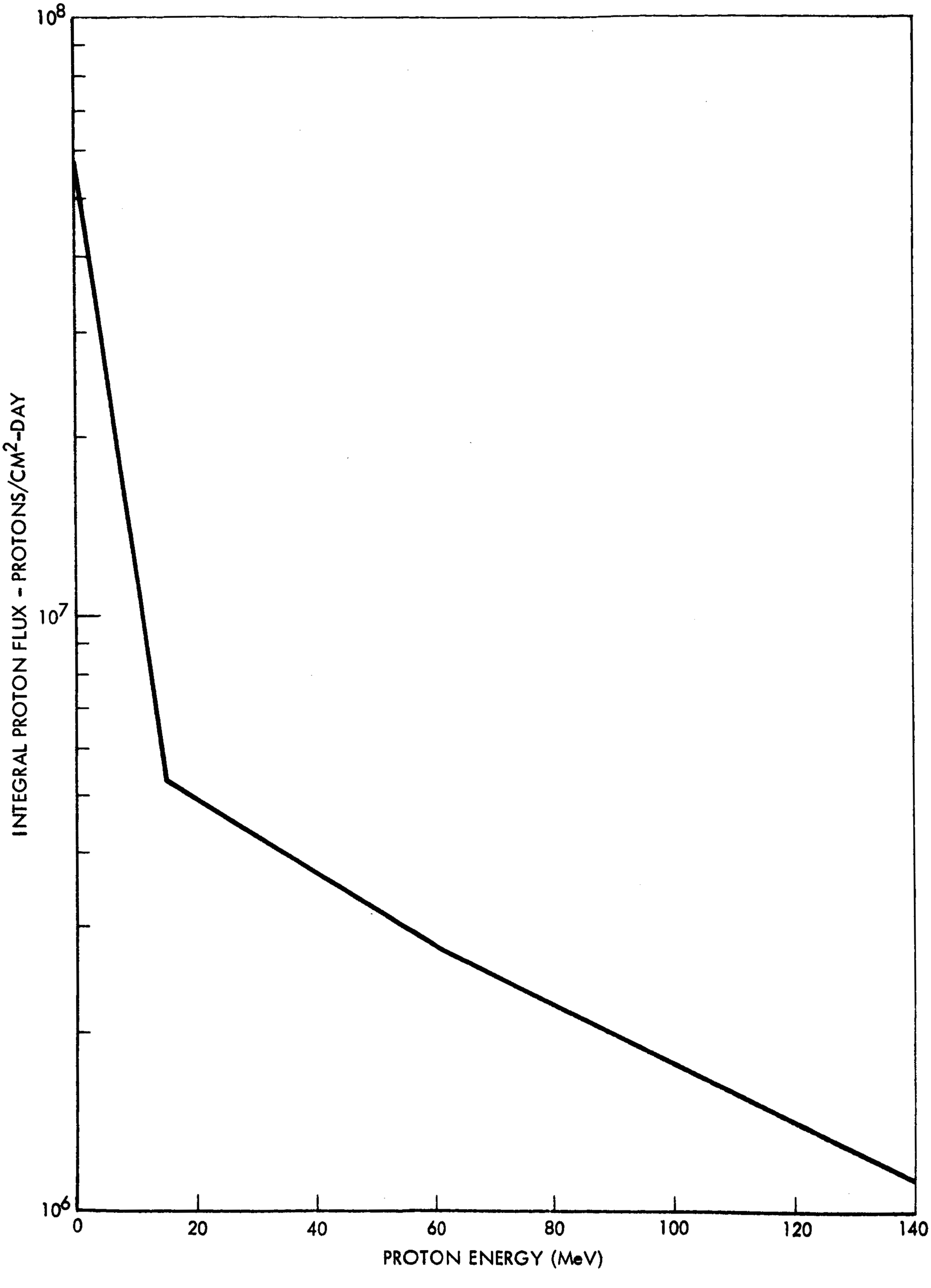

FIGURE 2 - INTEGRAL TRAPPED PROTON ENERGY SPECTRUM ENCOUNTERED IN CIRCULAR EARTH ORBIT WITH 300 NM ALTITUDE AND 30° INCLINATION.

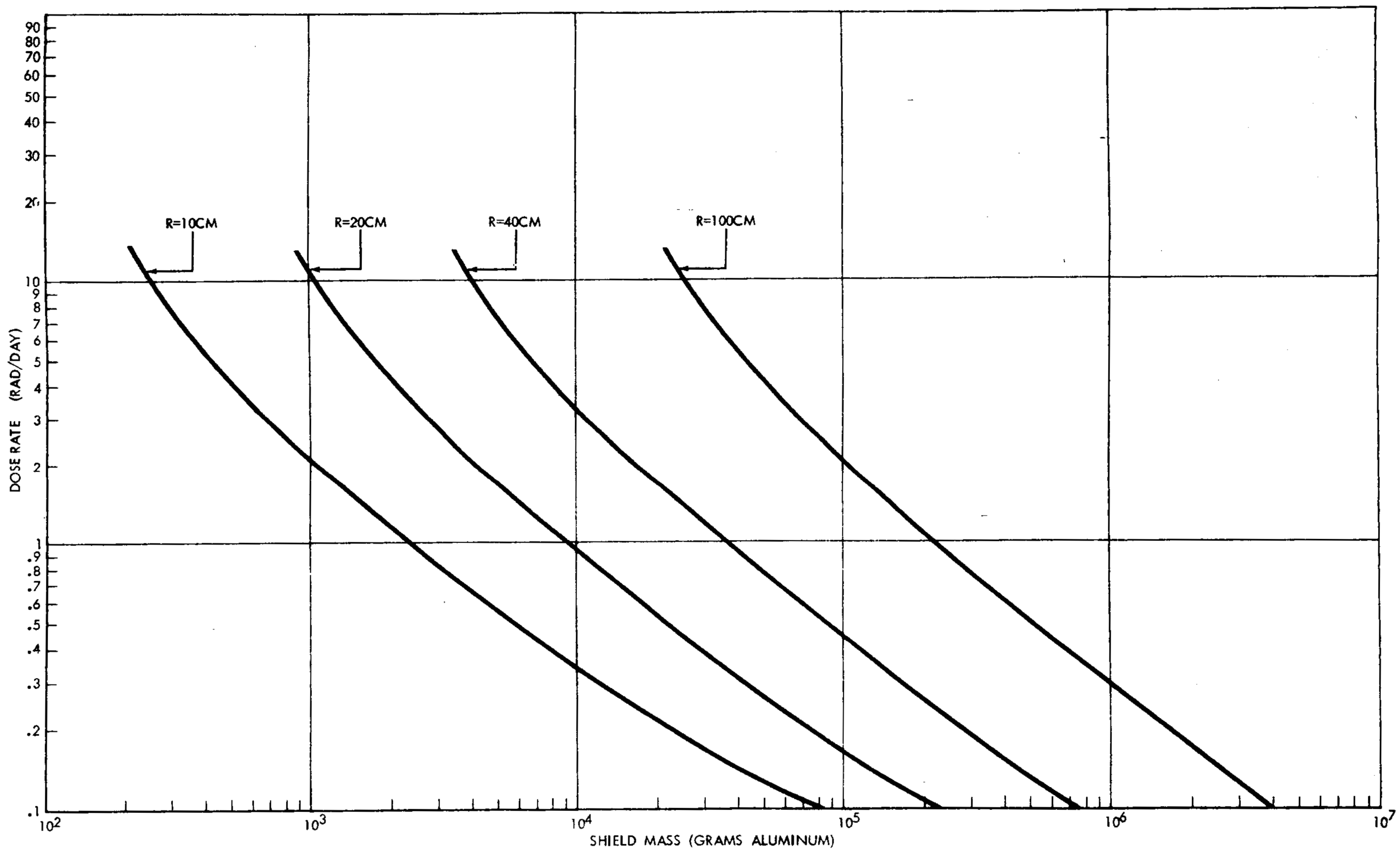

FIGURE 3 - MASS OF ALUMINUM REQUIRED TO SHIELD SPHERICAL CASKETS IN 30 NM, 30° CIRCULAR ORBIT TO A GIVEN DOSE RATE LEVEL.

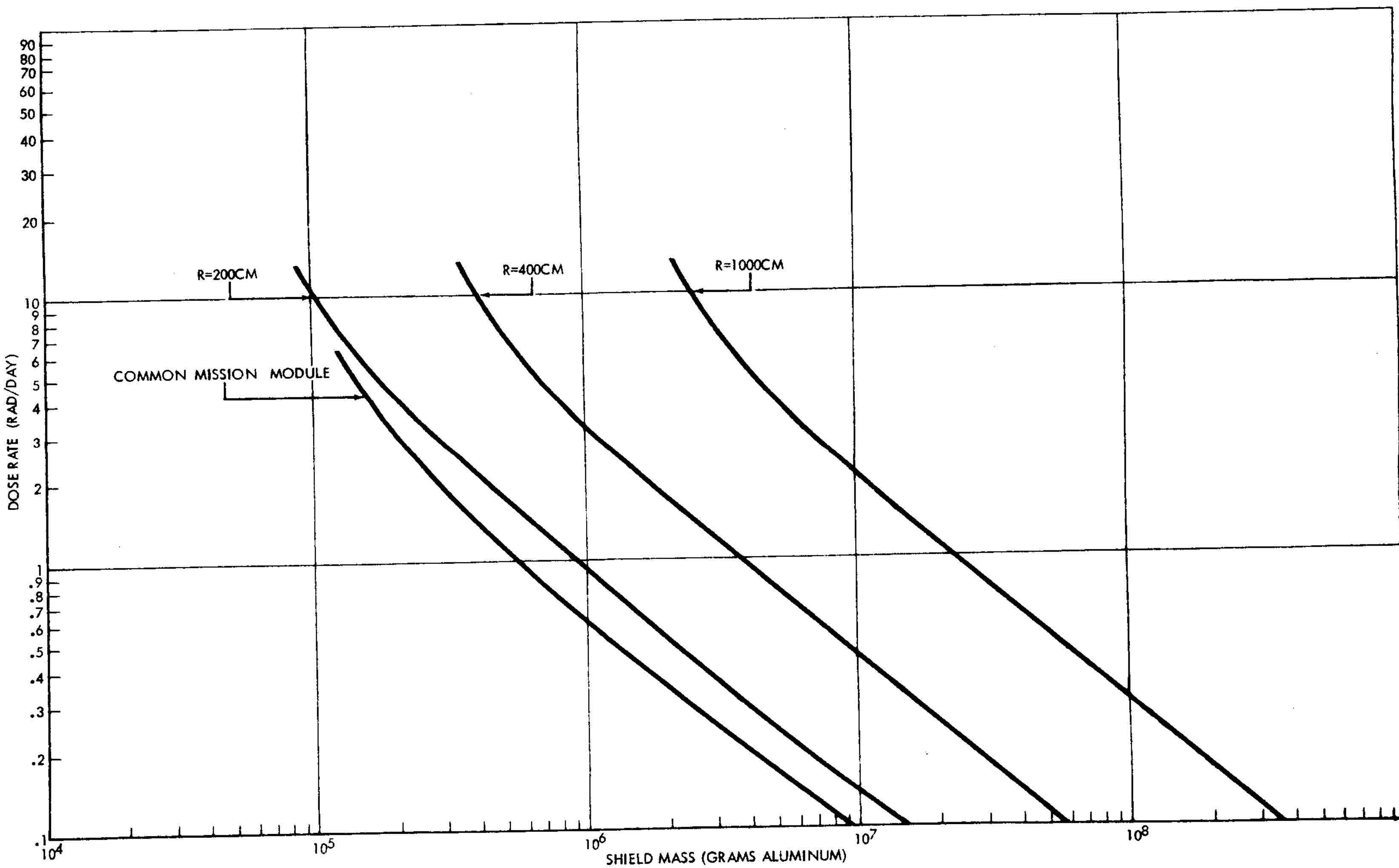

FIGURE 4 - MASS OF ALUMINUM REQUIRED TO SHIELD SPHERICAL CASKETS AND MODEL COMMON MISSION MODULE IN 300 NM, 30° CIRCULAR ORBIT TO A GIVEN DOSE RATE LEVEL.

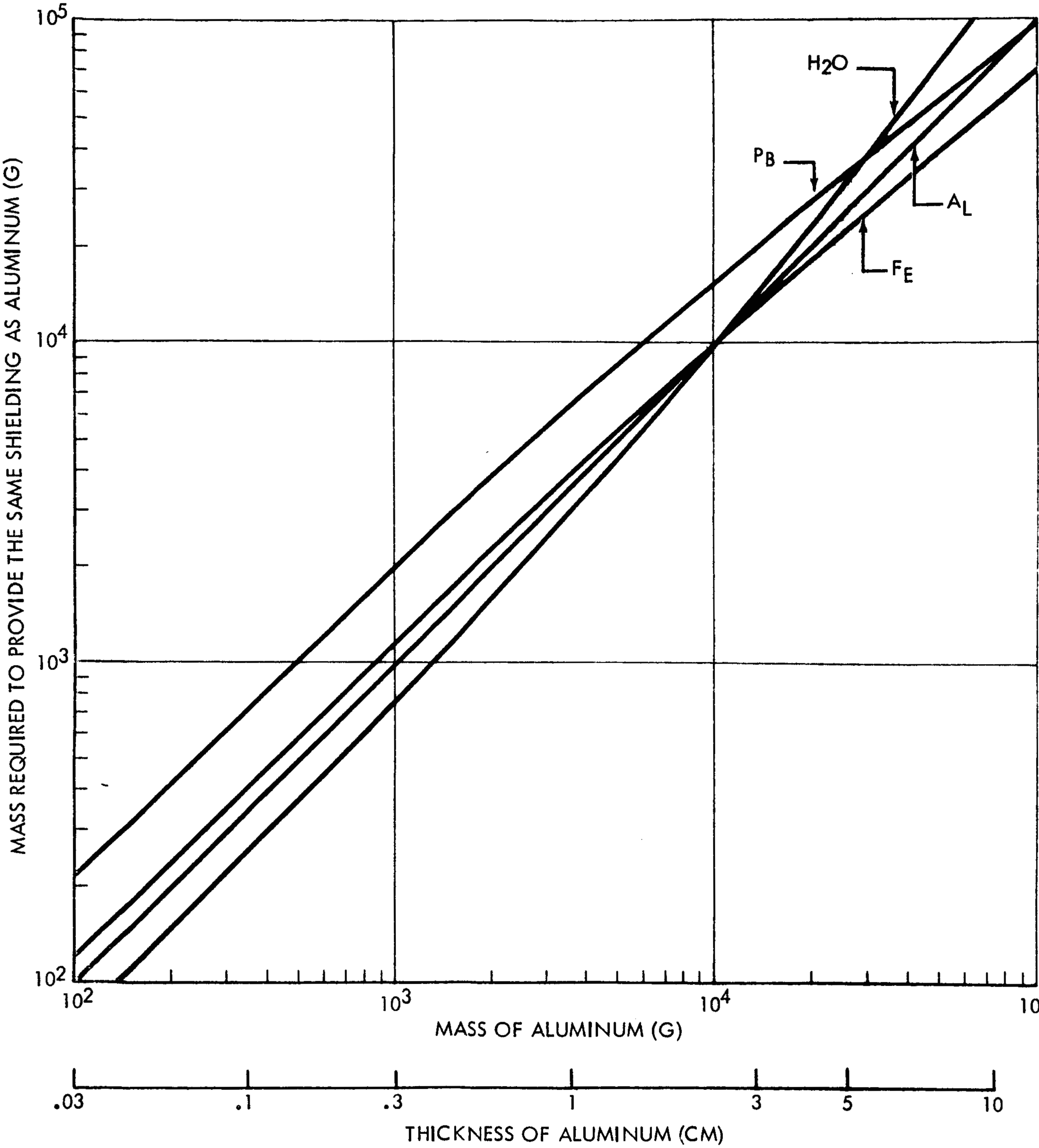

FIGURE 5 - COMPARISON OF MASS OF LEAD, IRON, ALUMINUM AND WATER AS SHIELDING MATERIALS FOR A SPHERICAL CAVITY WITH INSIDE RADIUS EQUAL TO 10 CM.

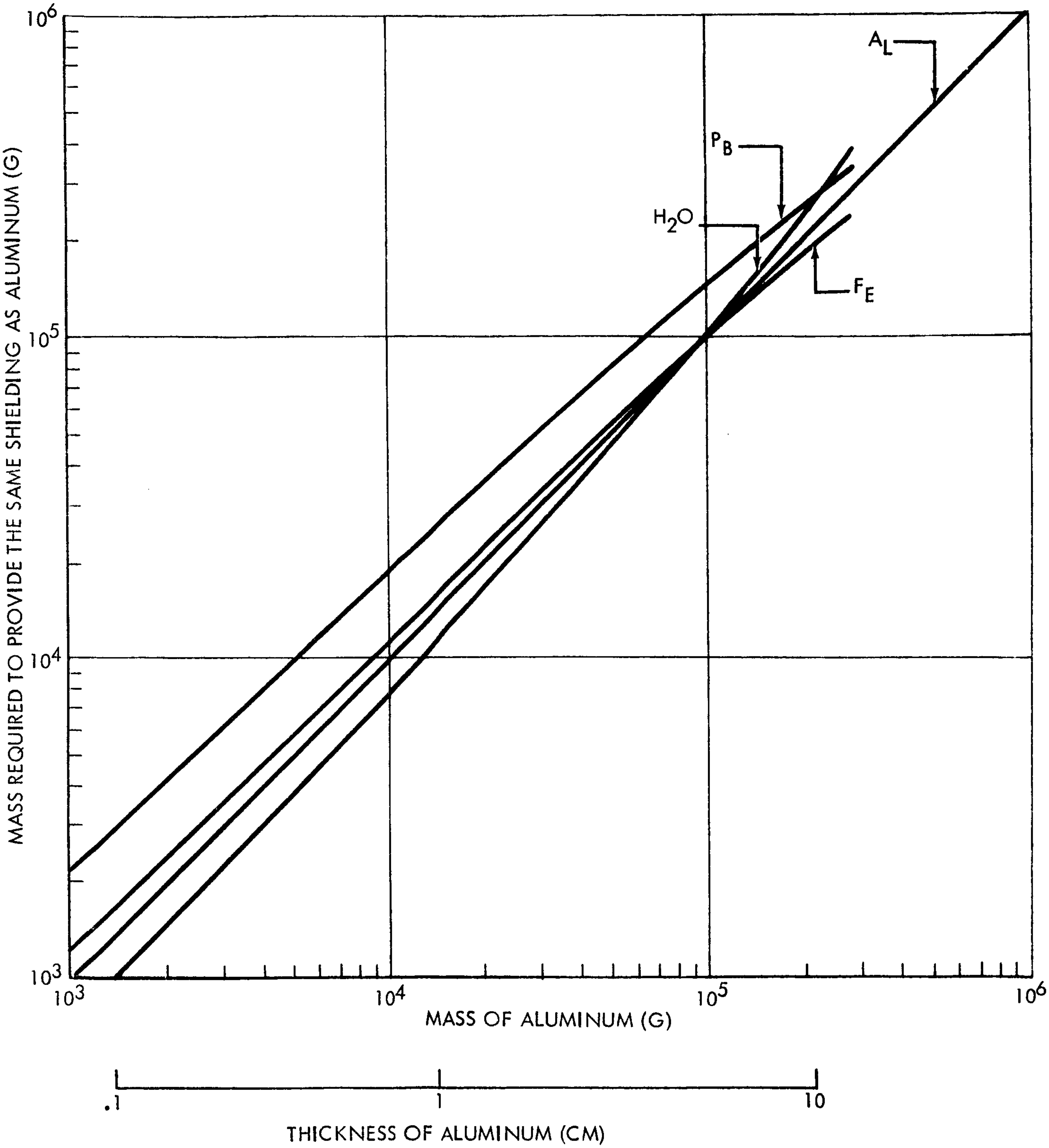

FIGURE 6 - COMPARISON OF MASS LEAD, IRON, ALUMINUM AND WATER AS SHIELDING MATERIALS FOR A SPHERICAL CAVITY WITH INSIDE RADIUS EQUAL TO 20 CM.

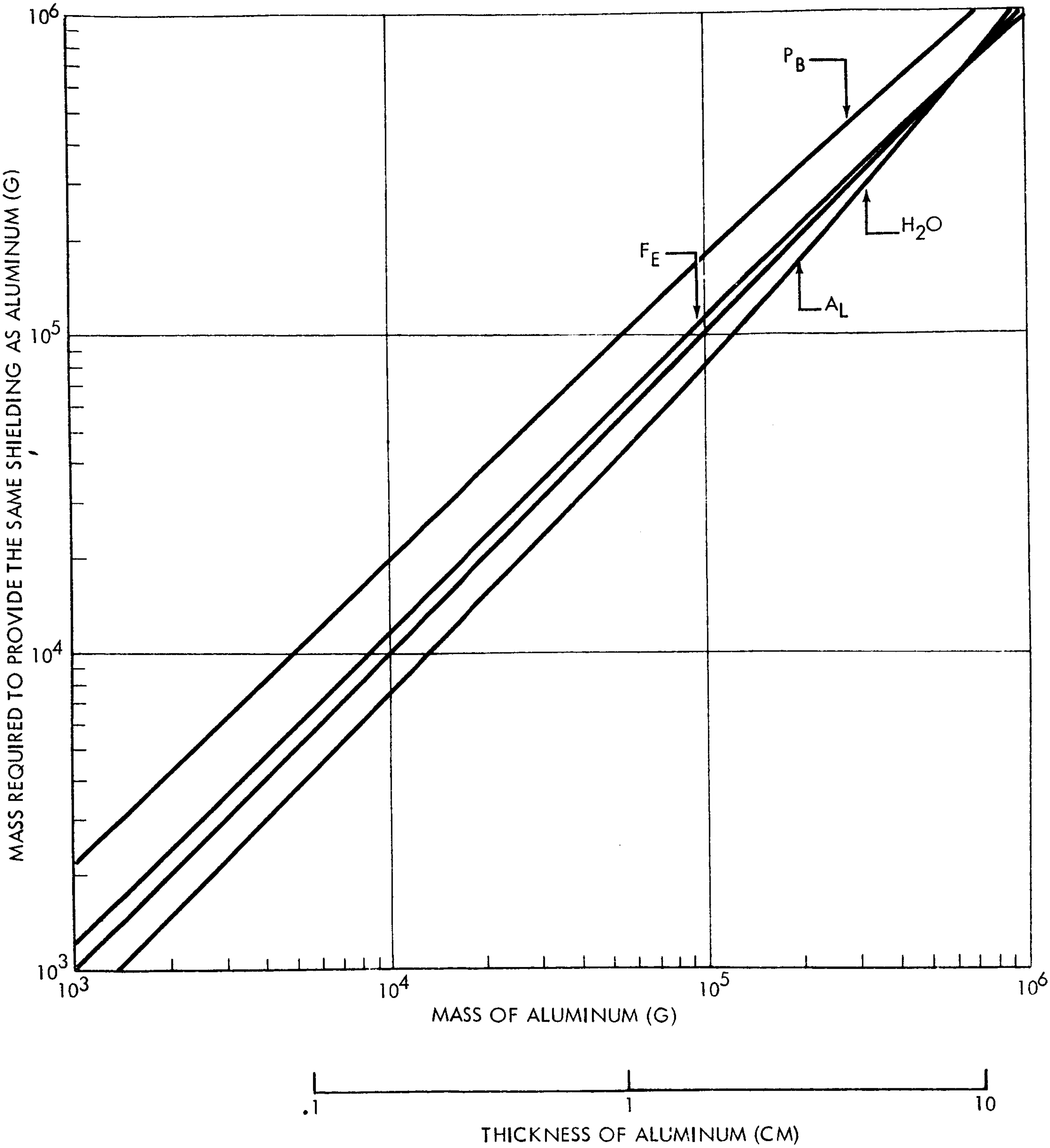

FIGURE 7 - COMPARISON OF MASS OF LEAD, IRON, ALUMINUM AND WATER AS SHIELDING MATERIALS FOR A SPHERICAL CAVITY WITH INSIDE RADIUS EQUAL TO 40 CM.

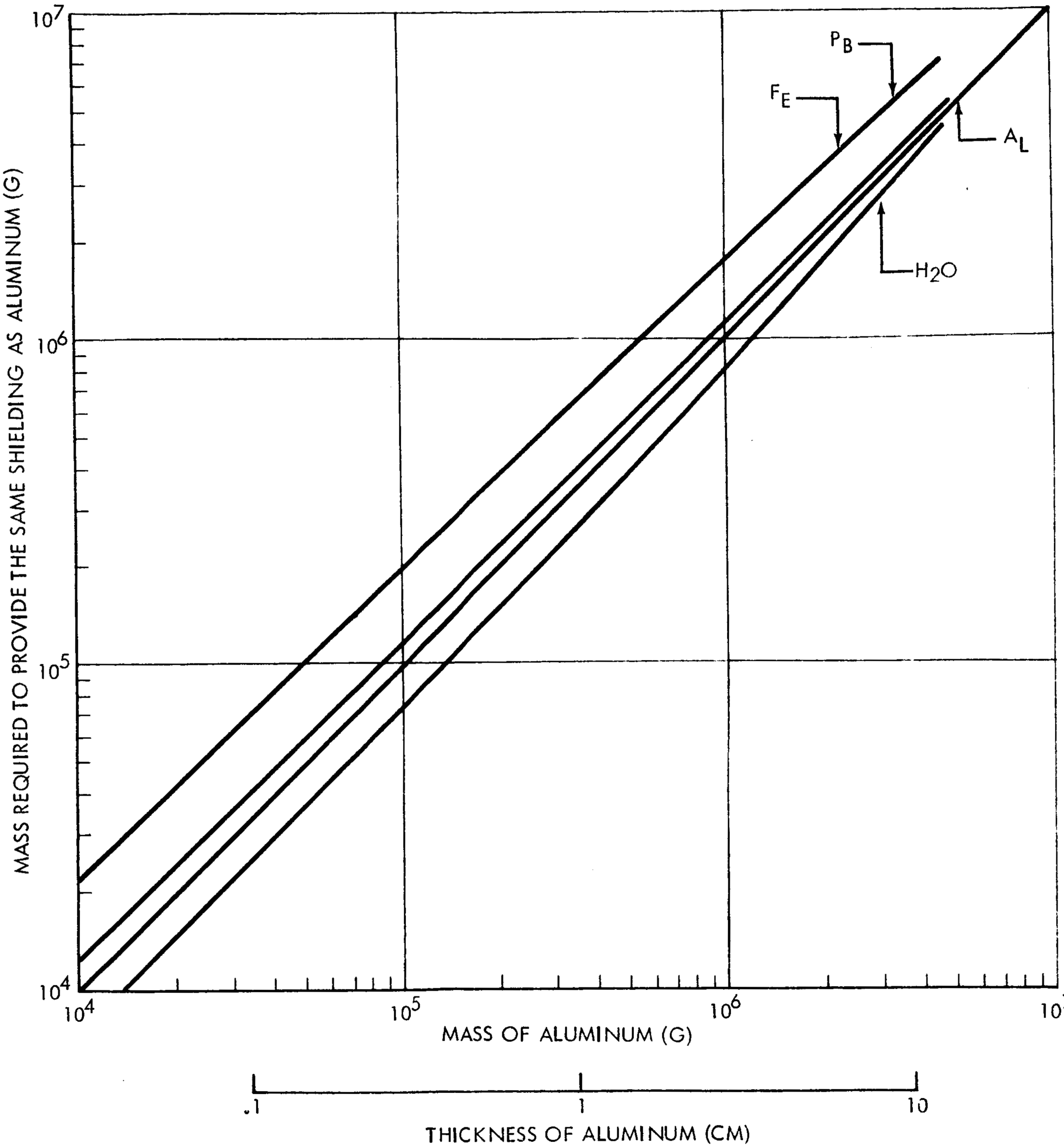

FIGURE 8 - COMPARISON OF MASS OF LEAD, IRON, ALUMINUM AND WATER AS SHIELDING MATERIALS FOR A SPHERICAL CAVITY WITH INSIDE RADIUS EQUAL TO 100 CM .

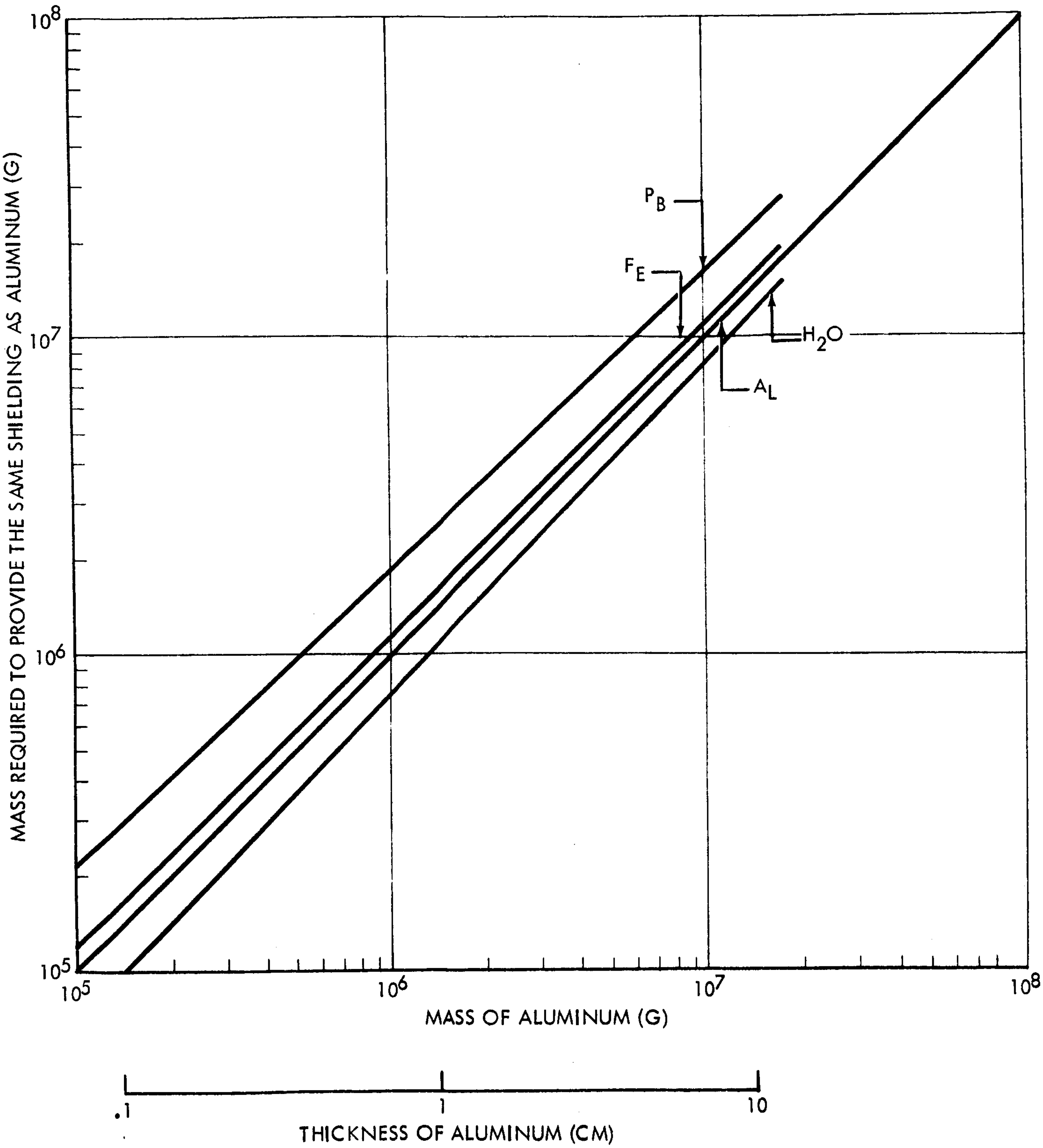

FIGURE 9 - COMPARISON OF MASS OF LEAD, IRON, ALUMINUM AND WATER AS SHIELDING MATERIALS FOR A SPHERICAL CAVITY WITH INSIDE RADIUS OF 200 CM.

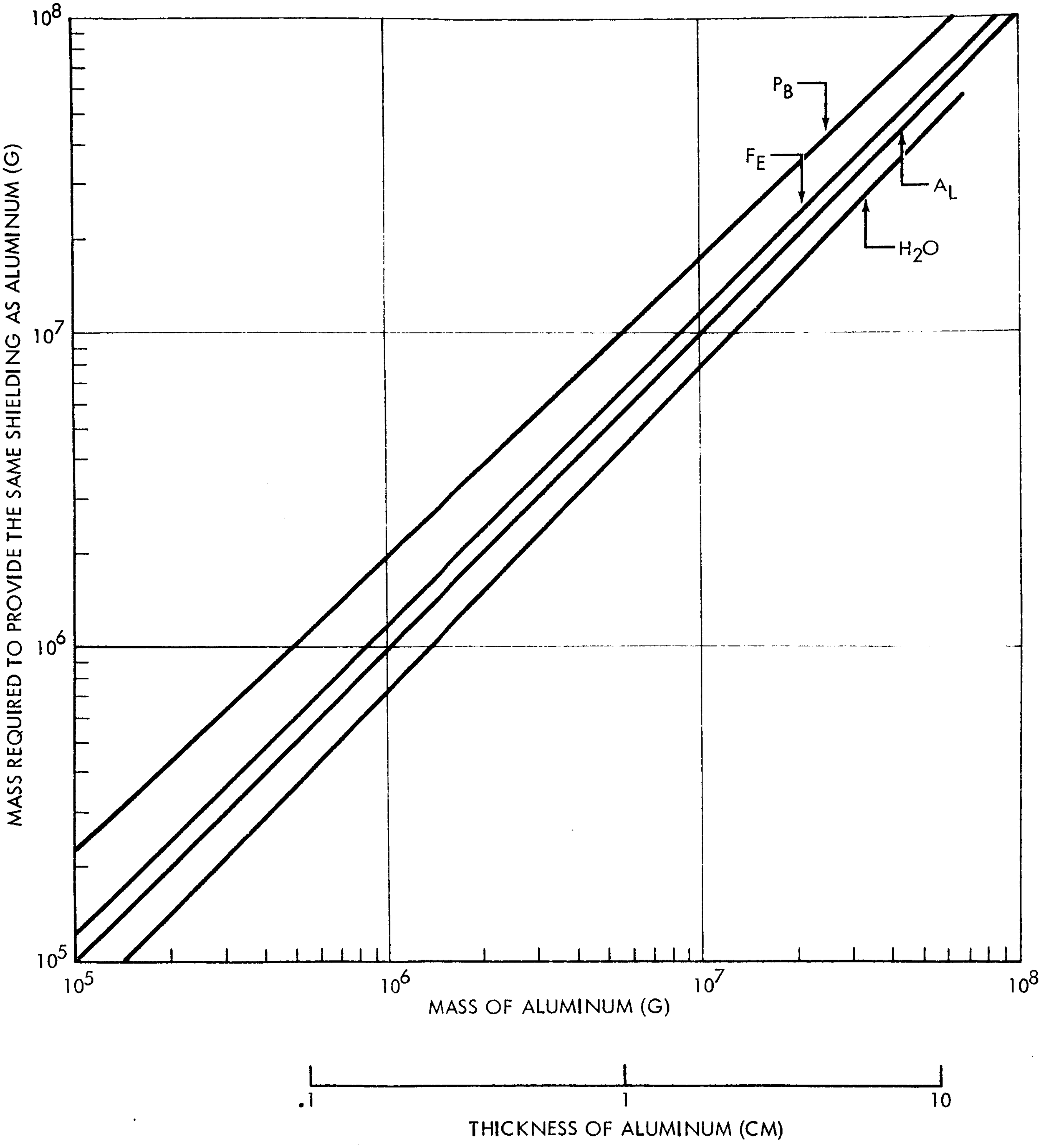

FIGURE 10 - COMPARISON OF MASS OF LEAD, IRON, ALUMINUM AND WATER AS SHIELDING MATERIALS FOR A SPHERICAL CAVITY WITH INSIDE RADIUS EQUAL TO 400CM.

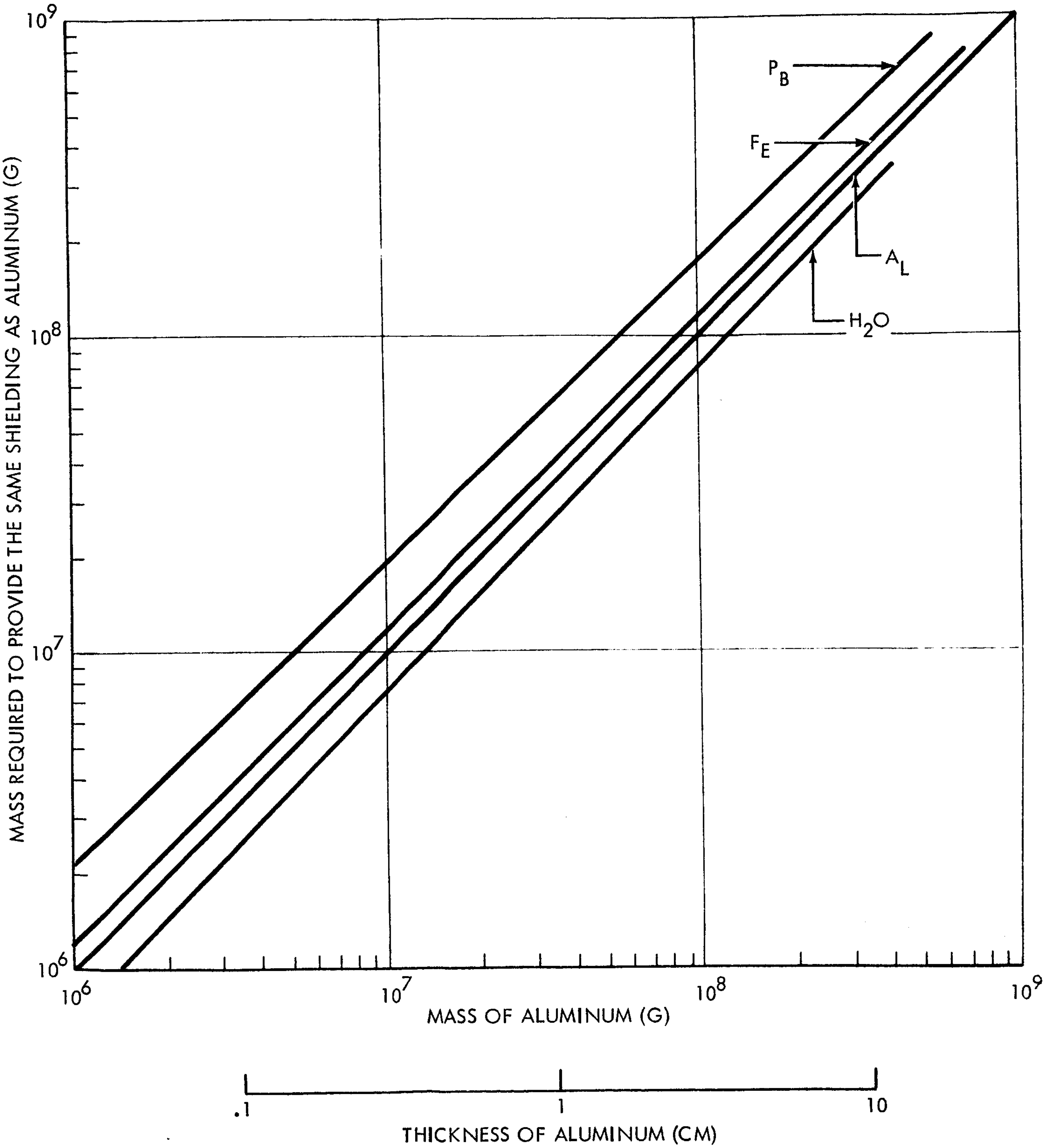

FIGURE 11 - COMPARISON OF MASS OF LEAD, IRON, ALUMINUM AND WATER AS SHIELDING MATERIALS FOR A SPHERICAL CAVITY WITH INSIDE RADIUS EQUAL TO 1000 CM.

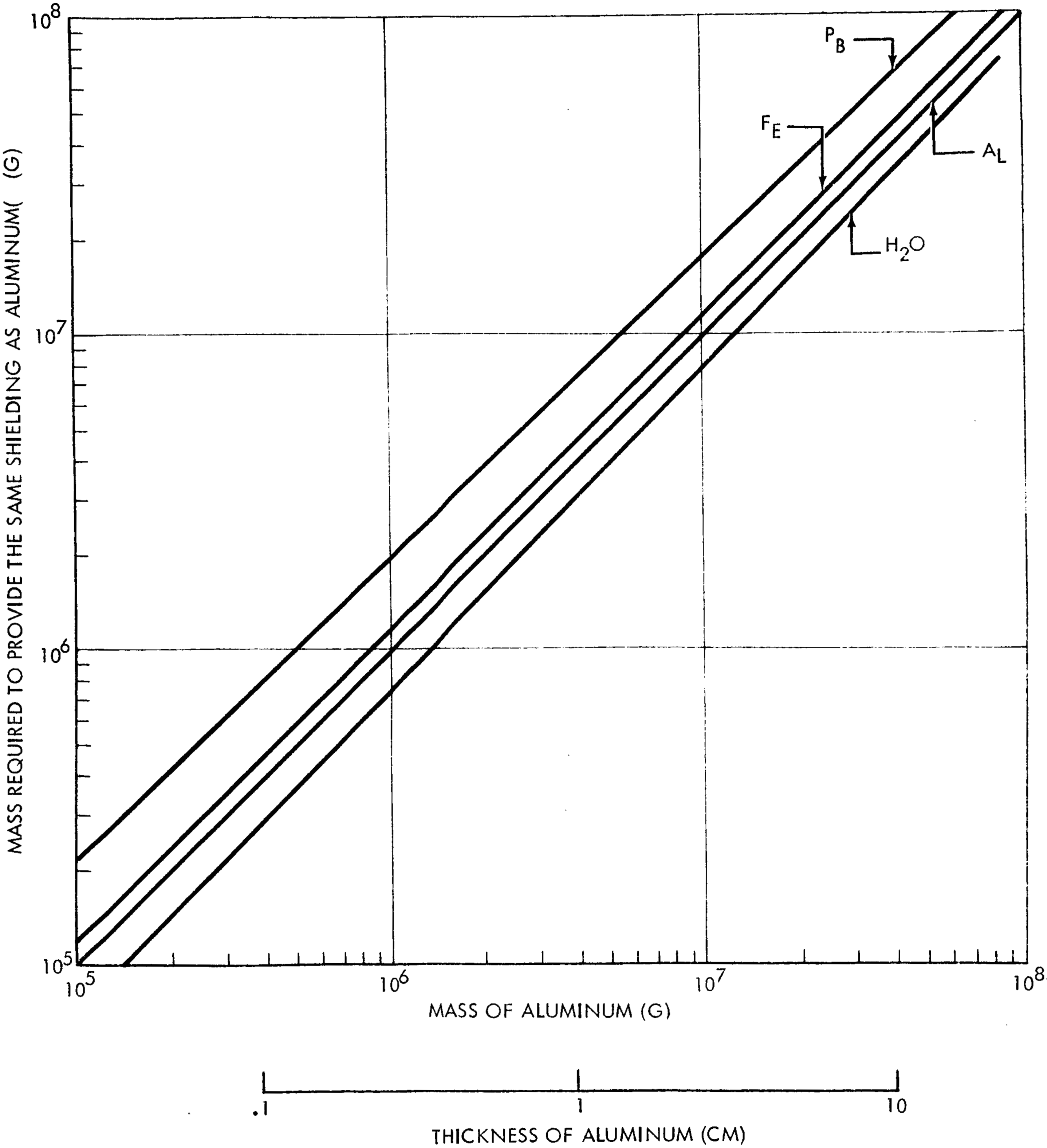

FIGURE 12 – COMPARISON OF MASS OF LEAD, IRON, ALUMINUM AND WATER AS SHIELDING MATERIALS FOR A MODEL COMMON MISSION MODULE.